Extensions to the Galileo Attitude Control System for the Probe Mission

Tracy Neilson
Kathryn Hilbert

1. Introduction

On July 12, 1995 the Galileo spacecraft released an atmospheric entry probe on an impact trajectory with Jupiter. Both the Probe and the Orbiter spacecraft will arrive at Jupiter on December 7, 1995 for a 75 minute rendezvous in which Jovian atmospheric data will be relayed from the Probe instruments to the Orbiter as the Probe enters and descends into Jupiter's atmosphere. Figure 1 illustrates both the Probe's and the Orbiter's trajectories on Arrival Day.

Jupiter Arrival (12/7/95) - **Pole View:**

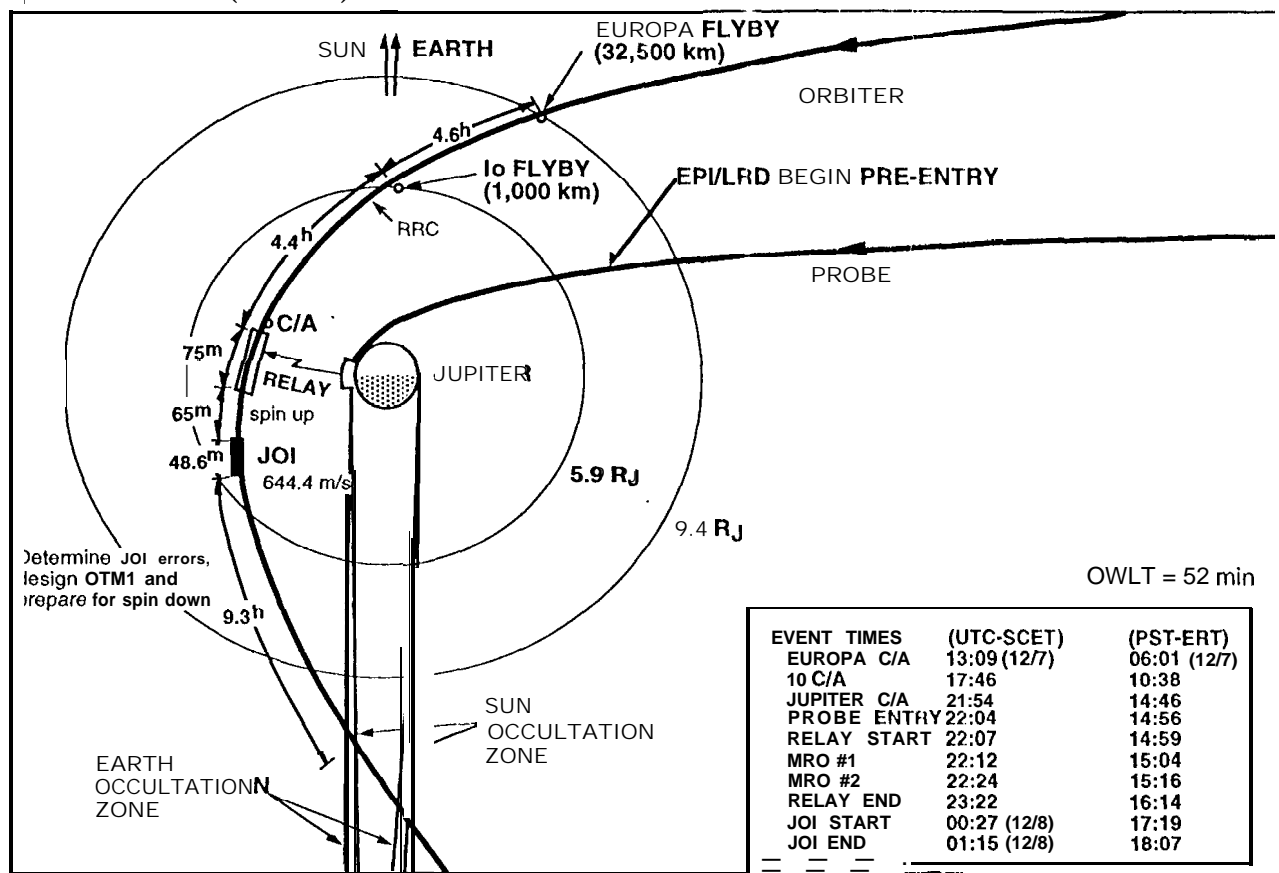| EVENT TIMES	(UTC-SCET)	(PST-ERT)
EUROPA C/A	13:09 (12/7)	06:01 (12/7)
10 C/A	17:46	10:38
JUPITER C/A	21:54	14:46
PROBE ENTRY	22:04	14:56
RELAY START	22:07	14:59
MRO #1	22:12	15:04
MRO #2	22:24	15:16
RELAY END	23:22	16:14
JOI START	00:27 (12/8)	17:19
JOI END	01:15 (12/8)	18:07

Figure 1: Jupiter arrival day activities

To accomplish this feat requires accurate pointing of a Relay Radio Antenna (RRA) mounted on the despun section of the Orbiter. In addition, Galileo Mission guidelines dictate that the pointing of the RRA and the acquisition of the Probe Relay data must be guaranteed even in the presence of single point failures. This project requirement is particularly demanding in light of the fact that the Probe Relay portion of the Galileo mission will occur within the most severe radiat ion environment (< 4 times the radius of Jupiter, Rj) ever experienced by an interplanetary spacecraft,

To provide the necessary robustness and single fault tolerance, the existing attitude determination algorithms were modified and a completely new method for controlling the position of the stator based on sun sightings was designed and implemented within the spacecraft's flight computer. This paper will describe the design, development, ground testing, and in-flight testing of the One Star Attitude Determination (OSAD) and the Acquisition Sensor Attitude Determination (ASAD) algorithms.

2. Galileo Attitude Determination and Control

The dual-spin Galileo spacecraft, shown in figure 2, requires autonomous attitude determination and control for its three main structural components: rotor, stator, and scan platform. Onboard autonomous attitude determination for all three components is done using data from three different sensors: a rotor mounted star scanner which detects stars as the rotor rotates about the spin axis, a pair of two-degree-of-freedom rate gyros mounted on the scan platform, and angle encoders which measure the positions of the Spin Bearing Assembly (SBA) and Scan Actuator Subassembly (SAS).
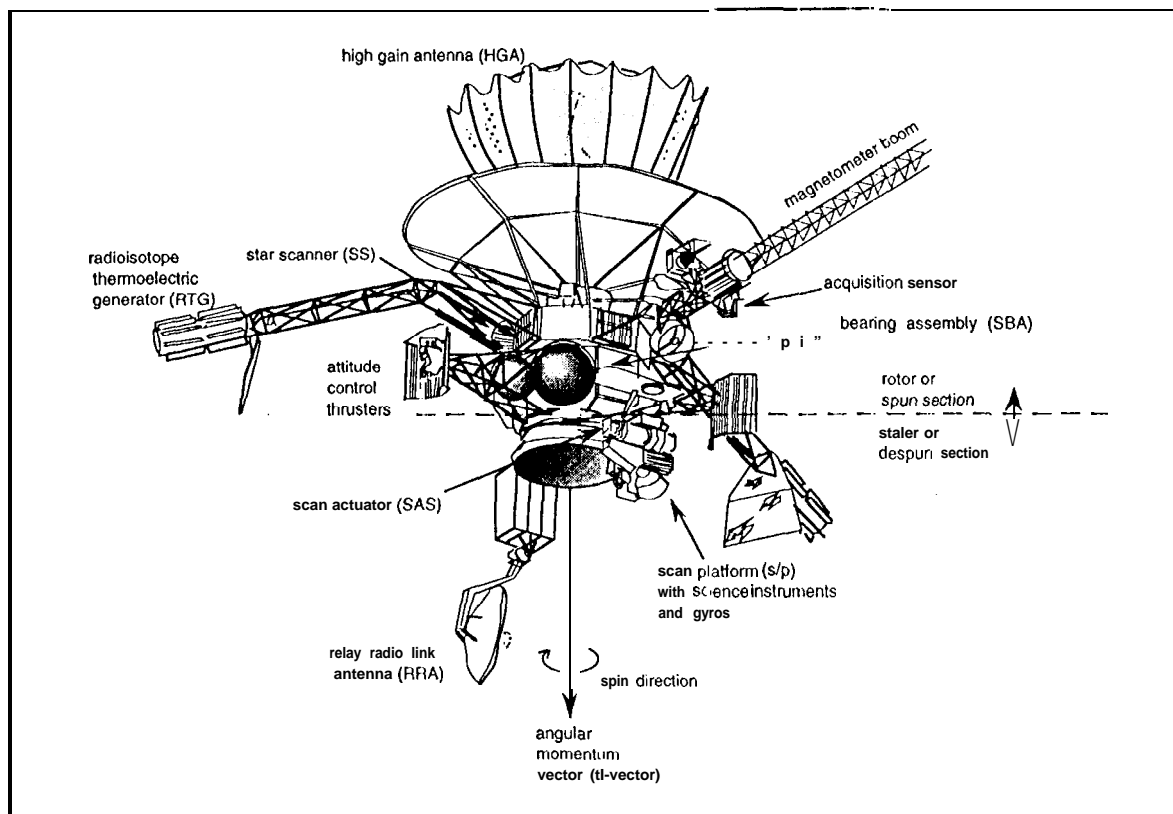

Figure 2: Galileo Spacecraft

Two options exist in the Attitude and Articulation Control Subsystem (AACS) flight software (FSW) for attitude determination during dual-spin operations. The primary method for quiescent interplanetary cruise operations (i.e. Cruise mode) is to use the star scanner and SA S/SBA encoder data to provide rotor and platform attitude estimates. The star identification algorithms process star scanner data to provide rotor attitude and spin rate estimates. Normally, a minimum of two stars are required for rotor attitude estimation. Encoder data provides the relative orientations and rates of the rotor, stator, and scan platform using estimates of the encoder angle rates.

The primary attitude determination method used for encounters and spacecraft maneuvers (i.e. Inertial mode) is done using a combination of gyro and star scanner data. However, the Inertial mode attitude determination algorithm requires an initial celestial platform attitude estimate in order to function. Gyro outputs are then integrated to maintain continuous knowledge of the scan platform orientation and rate in inertial coordinates. Drift in the gyro-based attitude estimate is corrected for using star attitude estimates, if available.

During Probe Relay. it is essential to maintain an attitude estimate to control the inertial clock orientation (rotation of the stator with respect to the rotor) of the RRA. This control mode is called stator pointing and is available in either Cruise or Inertial modes. The nominal plan for Probe Relay is to configure the spacecraft in Inertial mode and use the gyros as the primary source for attitude determination.

Unfortunately, an AACS Power On Reset (POR) will cause a complete reinitialization of the AACS FSW, the gyros to be powered off, and a temporary loss of clock control. Following such an event, the AACS FSW must autonomously. recalculate the inertial rotor and platform attitudes and reposition the stator to re-establish the relay radio link. Similarly, there are single point failures in the AACS hardware which could lead to an autonomous abort from Inertial mode to Cruise mode and a powering off of the gyros. In order to provide single point tolerance during probe Relay, therefore, requires that more than one source of *reliable* attitude determination information be available. It was this requirement which led to the development of the One Star Attitude Determination (OSAD) and Acquisition Sensor Attitude Determination (ASAD) algorithms.

3. One Star Attitude Determination (OSAD)

Although extensive analysis, testing, and redesign of the star scanner hardware and software was performed prior to the launch of Galileo to ensure radiation hardness, concerns about the robustness and reliability of the star identification algorithms within 10 Rj were raised post launch. These concerns were brought about by a series of star related flight anomalies which occurred shortly after launch (Ref 1). The resolution of these anomalies led to a better understanding of the limitations of the star identification algorithms used for both spin rate and attitude estimation.

Extensive radiation tests performed in late 1993 using flight spare star scanner hardware and extensive review of Voyager and Pioneer flight data confirmed that the only star in the star scanner's field of view at the Probe Relay attitude that could be reliably detected in the presence of high radiation was Canopus. This finding led to an extension of the existing attitude determination algorithms, called OSAD. The fundamental objective of OSAD is to allow the existing star processing and celestial attitude determination algorithms to function using only one star.

Once enabled via a ground controlled flag, the OSAD algorithm freezes the angular momentum vector estimate to the commanded Relay H-vector direction and uses the brightest star in the star scanner field of view (Canopus) as a clock reference. Thus the stator position can be held at the commanded clock angle. The H-vector is frozen to prevent the estimate from diverging about the single star vector. The only effect that the OSAD algorithm has on Inertial mode attitude determination is to prevent corrections to the gyro-based attitude estimate based on Canopus sightings. This is acceptable since the drift in the gyros is typically very small (.05 °/hr/gyro axis) and the gyros will have been calibrated just prior to Probe Relay.

4. Acquisition Sensor Attitude Determination (ASAD)

Unfortunately, the star scanner hardware radiation analysis and testing could not guarantee that even Canopus could be reliably identified in the Jovian radiation. "1 'herefore, attitude estimation using the Sun Acquisition Sensor was deemed a prudent secondary backup mode for Relay stator pointing control. The acquisition sensor detects the sun pulse each revolution and is already used by the FSW to compute a spin

rate estimate, as well as fire the O N thrusters to point the spacecraft at the. sun if a sun acquisition maneuver is requested. The same basic concept used forth; OSAD algorithm was applied-to develop the ASAD algorithm: use the commanded angular momentum vector and update the clock reference with sun sightings from the acquisition sensor. The acquisition sensor-based estimate is assigned the lowest priority attitude data source and will only be selected if neither gyro or star-based attitude estimates are available.

Figure 3 illustrates the various sources of attitude information which can be used for stator control,
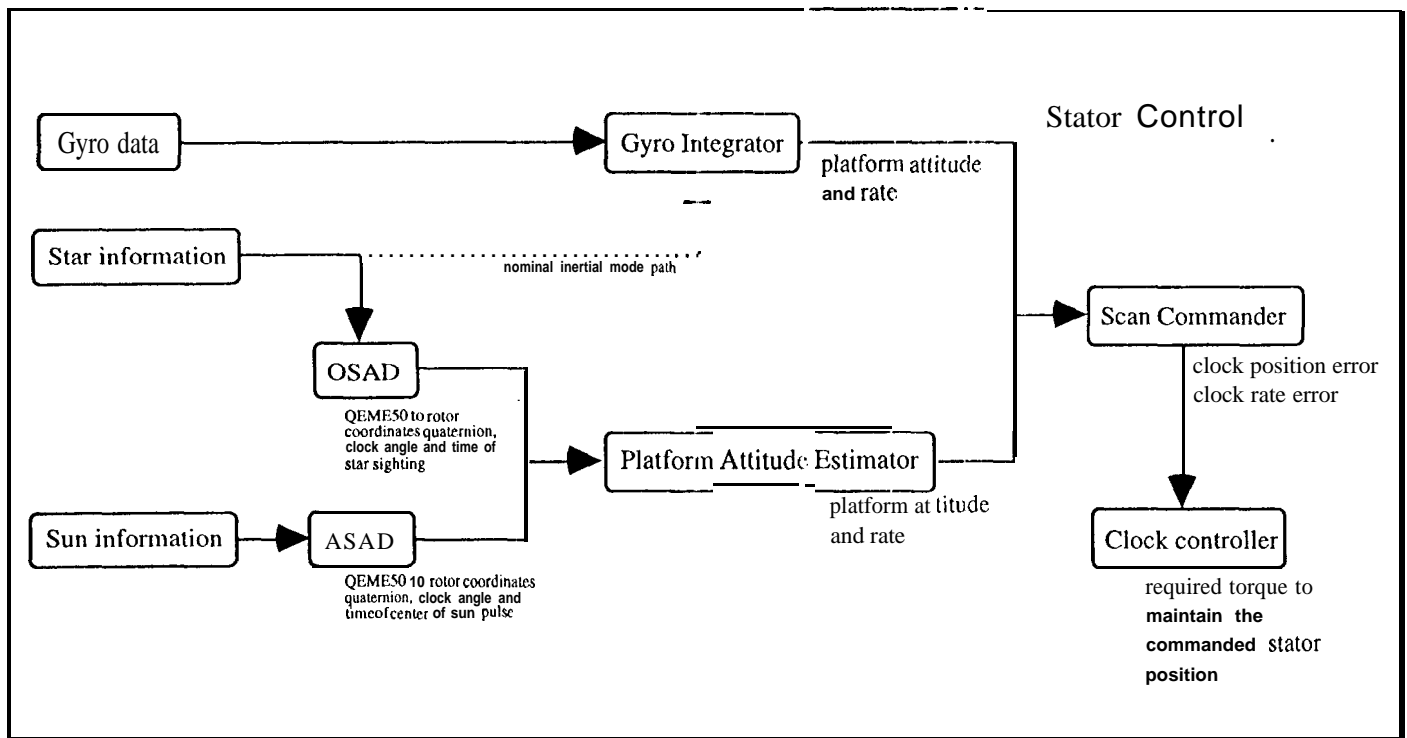
Figure 3: Stator Control Flow Chart

5. Ground Testing of OSAD and ASAD

The two new algorithms were extensively tested in the Galileo Integration Test Laboratory (ITL), commonly referred to as the testbed. This real time simulation facility includes the actual AACS HAL/S flight code, flight hardware spares, and support equipment/computers that simulate the rest of the spacecraft and external environment.

The test program involved simulation of the Probe Relay sequence of commands under nominal conditions and under numerous fault conditions (software and hardware PORS as well as gyro, actuator, star scanner, and sun acquisition sensor failures). The test results were analyzed and demonstrated that the new attitude determination capabilities provided the required single. fault tolerance for the critical Probe mission.

6. In-flight Test of OSAD and functional verification of ASAD

Due to the criticality of the Probe Relay phase of the mission, the Project elected to perform an in-flight demonstration on September 14, 1995 of the nominal gyro-based stat or pointing and OSAD stator pointing

capabilities. Additionally, ASAD data was collected to assess the functionality of this new algorithm. The results were excellent and it was determined that all three sources can meet the stator pointing requirement for the RRA of ±2. 10. Figure 4 shows a sample of the in-flight stator pointing performance data in both Inertial mode, using only the gyros for the attitude estimate, and in Cruise **mode,** using OSAD.

7. Summary

Two new methods of estimating and controlling the stator position during Probe Relay have been developed, tested, and implemented on the Galileo spacecraft. Both ground and in-flight tests have demonstrated that these two algorithms provide the necessary robustness and reliability that is required to guarantee the acquisition of the Probe relay data.

This paper will describe in detail the design philosophy, software implementation, and test program which was used in the development of the One Star and Acquisition Sensor Attitude Determination algorithms. Problems encountered during development and flight test will be described as well as the solutions to those problems. Optimization of both the ASAD and OSAD using actual flight data will also be presented,

8. Acknowledgements

References:

(1)   Merken, L. and Singh, G., Galileo Attitude Determination: Experiences with a Rotating Star Scanner, Paper 3rd International Symposium on Spacecraft Flight Dynamics, Sept. 30- Oct. 4, 1991.
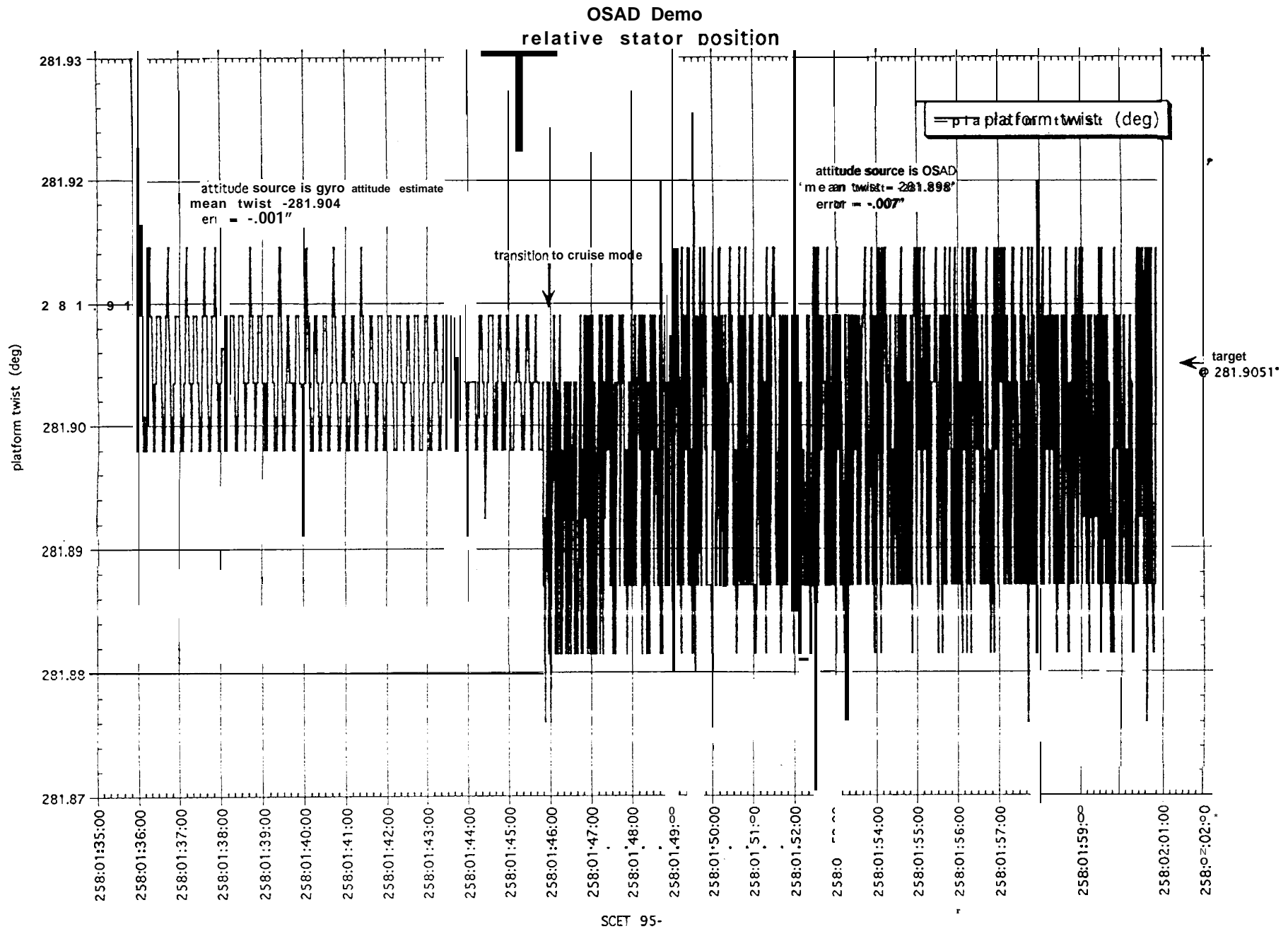
Figure 4: Flight data on stator position
for inertial mode, gyros only attitude estimate
and cruise mode OSAD pointing control